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Study of the Simplified Dynamic Thermal Network Model for the Hollow Block Ventilated Wall

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Abstract

With the growing building energy consumption, people have to pay more and more attention to adopt new methods, new techniques to save energy. The hollow block ventilated wall is a new building envelope with the cold air in summer and hot air in winter flowing into the cavity, which can carry away the cooling and heat stored in walls. The cooling and heating loads of the building can be greatly reduced or even eliminated by removing the outdoor environmental effects on the building envelope, it has important significance for building energy efficiency. To obtain the thermal performance of the hollow block ventilated wall, a simplified dynamic thermal network model using RC-network method is established in this study, and the parameters are optimized using genetic algorithm.

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Keywords: Hollow block ventilated wall; Simplified dynamic thermal network model; Parameter optimization; Frequency characteristic; Genetic algorithm

1. Simplified dynamic thermal network model for the hollow block ventilated wall

1.1. Heat transfer model

Currently, the most common size of hollow block brick is 390 × 190 × 190 (mm) small concrete block in the market. The hollow area ratio of the hollow blocks is about 25% ~ 50%. Here, a single hole hollow block is used for this study. Fig. 1 shows the typical cross section of the hollow block ventilated wall.

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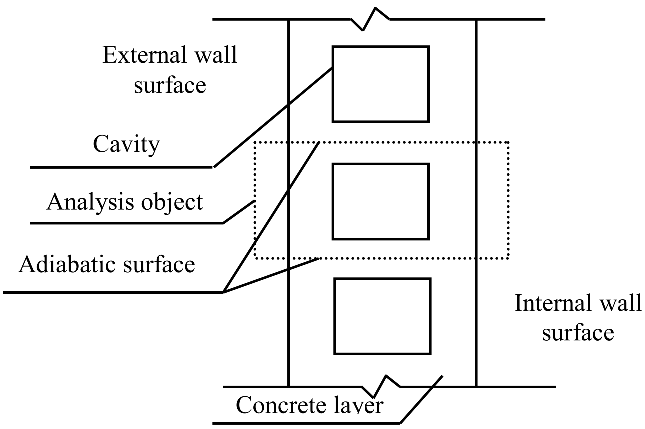

Fig. 1. Schematic of the cross section of the hollow block ventilated wall.

The envelope in the dotted box of Fig.1 is selected as the object of study, the top and bottom edges are adiabatic, left and right sides, respectively, are affected by solar air temperature and indoor temperature. Intercept a short height in the height direction with air temperature changes in this scale is neglected, and only the heat transfer in the length direction and the thickness direction is considered, therefore the heat transfer can be simplified as a two-dimensional heat transfer problem

1.2. Simplified dynamic thermal network model

The typical research object as shown in Fig. 2 (a) is simplified as the dynamic thermal network model in Fig. 2 (b), where *R* is the thermal resistance, *C* is the capacitance, *T* is the temperature. T_1 and T_2 are the temperatures of two assumed isothermal surface, and the distance from the two assumed isothermal surface to the outer surface and the inner surface is L_1 and L_4 respectively.

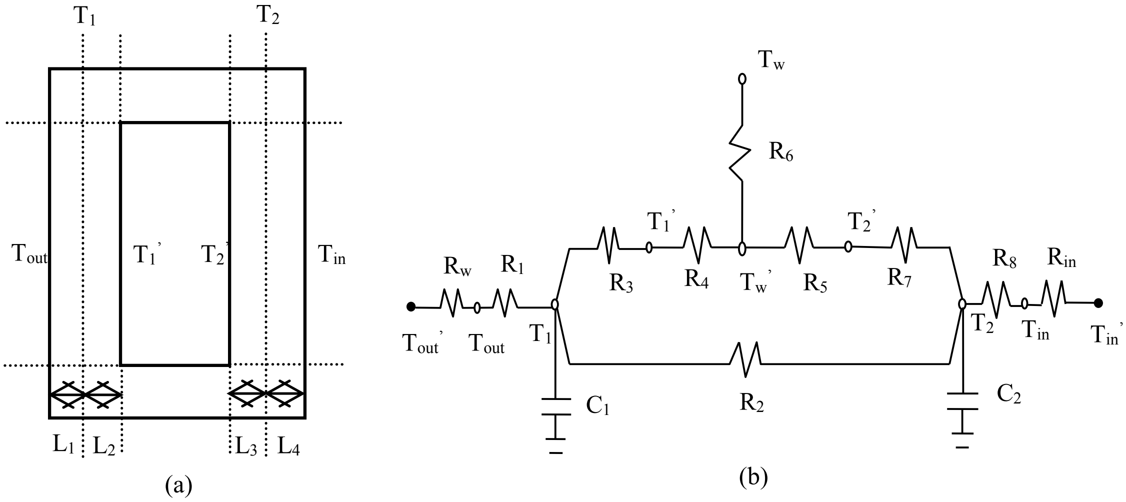

Fig. 2. Schematic of the simplified thermal model of the hollow block ventilated wall.

In Fig. 2, Tout is the temperature of the external wall surface, Tin is the temperature of the internal wall surface, Tw is the temperature of the air in the cavity, Tw' is the assumed temperature of the air in the cavity, Tout' is the solar air temperature, Tin' is the indoor air temperature. T1'and T2', are the temperatures of two surfaces of the cavity respectively. R is the heat resistance. As for the heat transfer in the cavity, the situation becomes more complicated. There exists convective heat transfer and radiation heat transfer. The equivalent thermal resistance of the cavity can be expressed in a resistor-triangle of two convection heat transfer resistance (Rc1, Rc2) and one radiation heat transfer resistance (Rr) as shown in Fig. 3(a), and the triangle network can be transformed to an equivalent star network according to Fig. 3(b), the equivalent heat resistance R4, R5 and R6 can be calculated as follows [1]:

$$R_4 = \frac{R_{c1} \times R_r}{R_{c1} + R_{c2} + R_r},\ R_5 = \frac{R_{c2} \times R_r}{R_{c1} + R_{c2} + R_r},\ R_6 = \frac{R_{c1} \times R_{c2}}{R_{c1} + R_{c2} + R_r}$$

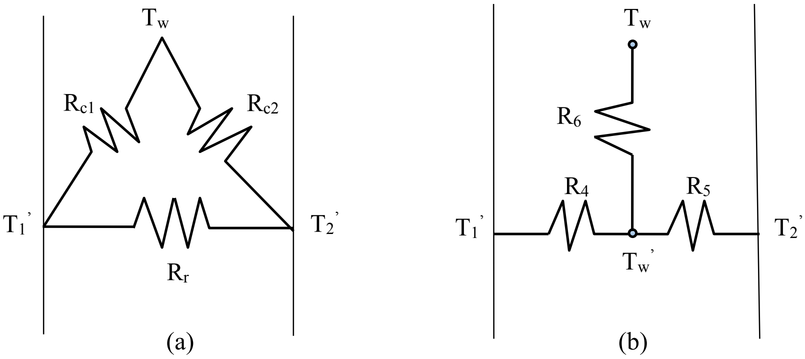

Fig. 3. The transformation of the equivalent thermal resistance in the cavity.

Considering the convection heat transfer of the external wall surface and internal wall surface with the air, the thermal equilibrium equations can be written as follows:

$$\frac{T_{out}^{'} - T_{out}}{R_w} = \frac{T_{out} - T_1}{R_1} \tag{1}$$

$$\frac{T_2 - T_{in}}{R_8} = \frac{T_{in} - T_{in}^{'}}{R_{in}} \tag{2}$$

$$A_1 C_1 \frac{dT_1}{dt} = A_1 \frac{T_{out} - T_1}{R_1} + 2A_3 \frac{T_2 - T_1}{R_2} + A_2 \frac{T_1^{'} - T_1}{R_3} \tag{3}$$

$$A_1 C_2 \frac{dT_2}{dt} = A_2 \frac{T_2^{'} - T_2}{R_7} + 2A_3 \frac{T_1 - T_2}{R_2} + A_1 \frac{T_{in} - T_2}{R_8} \tag{4}$$

$$\frac{T_1 - T_1^{'}}{R_3} = \frac{T_1^{'} - T_w^{'}}{R_4} \tag{5}$$

$$\frac{T_w^{'}-T_2^{'}}{R_5}=\frac{T_2^{'}-T_2}{R_7} \tag{6}$$

$$T_w^{'}\left(\frac{1}{R_4}+\frac{1}{R_5}+\frac{1}{R_6}\right)-\frac{T_1^{'}}{R_4}-\frac{T_2^{'}}{R_5}-\frac{T_w}{R_6}=0 \tag{7}$$

Where: A1, A2 and A3 are the corresponding heat transfer areas. The matrix equation (15) can be obtained by simple transform and operation of equation (1)-(7). The temperature in complex domain can be expanded as real component and image component as Equation (8). The variables u and v can be described in terms of and PA as Equation (9). Then, the amplitude and phase angle of the frequency characteristics can be easily obtained as Equation (10) based on the solved u and v.

$$T=\overline{T}\exp(i(\omega t+\Phi))=\overline{T}\exp(i\Phi)\exp(i\omega t)=(u+iv)\exp(i\omega t) \tag{8}$$

$$u=\overline{T}\cos\Phi, v=\overline{T}\sin\Phi \tag{9}$$

$$AM=\sqrt{u^2+v^2}, PA=\arctan\frac{v}{u} \tag{10}$$

Where T is the temperature in time domain, AM is the amplitude, PA is the phase angle.

2. Parameter optimization of the RC model by using GA

How to accurately determine the parameters (thermal resistances and capacitance) are very difficult, but these parameters are very important to the accuracy of the simplified model. It is necessary to optimize these parameters and the genetic algorithm (GA) is a nice choice. Genetic Algorithm (GA) is a method of searching the optimal solution by simulating biological evolution process. In recent years, it has been widely used in the field of building physics and HVAC. In this paper, we use the frequency characteristic of the hollow block ventilation wall which is calculated by the frequency-domain finite-difference (FDFD) model (theoretical model) as a reference to optimize the parameters of the RC model by using GA.

$$J(R_1,R_7,C_1)=\sum_{n=1}^{N}\sum_{m=1}^{3}\left\{\begin{array}{l}\left[W_{m,X}^{AM}\left|AM(G_{m,X}(j\omega_n))-AM(G_{m,X}^{'}(j\omega_n))\right|+W_{m,X}^{PA}\left|PA(G_{m,X}(j\omega_n))-PA(G_{m,X}^{'}(j\omega_n))\right|\right]+\\ \left[W_{m,Y}^{AM}\left|AM(G_{m,Y}(j\omega_n))-AM(G_{m,Y}^{'}(j\omega_n))\right|+W_{m,Y}^{PA}\left|PA(G_{m,Y}(j\omega_n))-PA(G_{m,Y}^{'}(j\omega_n))\right|\right]+\\ \left[W_{m,Z}^{AM}\left|AM(G_{m,Z}(j\omega_n))-AM(G_{m,Z}^{'}(j\omega_n))\right|+W_{m,Z}^{PA}\left|PA(G_{m,Z}(j\omega_n))-PA(G_{m,Z}^{'}(j\omega_n))\right|\right]\end{array}\right\} \tag{11}$$

$$f(R_1,R_7,C_1)=\frac{1}{J(R_1,R_7,C_1)} \tag{12}$$

$$\begin{cases}0<R_1<R_l\\0<R_7<R_r\\0<C_1<C_t\end{cases} \tag{13}$$

$$\begin{cases}R_1+R_3=R_l\\R_7+R_8=R_r\\C_1+C_2=C_t\end{cases} \tag{14}$$

The frequency characteristics with the theoretical model are used as objective for the frequency characteristics of the simplified RC model for optimization. The Equation (11) represents the objective function of such optimization. The fitness function f is expressed as Equation (12), which is the reciprocal of Equation (11). The individual resistances and capacitances with the constraints are shown in Equation (13) and Equation (14), which are determined by the structure of the wall. In Equation (11)-(14), J is the objective function, AM is the amplitude, PA is phase angle, Gm (jωn) is the predicted frequency characteristic by using the RC model, Gm' (jωn) is the predicted frequency characteristic by using the FDFD model. The subscript X indicates the heat flux frequency characteristics on the external wall surface, Y indicates the frequency characteristics on the internal wall surface, Z indicates the frequency characteristics on the cavity surface. W is the weighting factor. The subscript m indicates the disturbance. Rl is the thermal resistance of the left concrete of the hollow block. Rr is the thermal resistance of the right concrete of the hollow block. Ct is the total thermal capacitance of concrete of the hollow block.

According to Equation (14), R3, R8 and C2 can be obtained after the calculated parameters R1, R7 and C1. The equivalent heat resistance R4, R5, R6 and thermal resistance R2 can also easy to obtain when the physical parameters is given.

To analyze the frequency characteristics of the hollow block ventilated wall, usually three disturbances (i.e., the solar air temperature disturbance, the indoor air temperature disturbance, and the cavity surface temperature disturbance) are imposed on these surfaces respectively. The combinations of these three disturbances are as follows [2]. (1) The solar air temperature is regarded with the amplitude of 1, the phase angle of 0, and the frequency of ω, and the remained two disturbances are assumed to be zero. (2) The indoor air temperature is regarded with the amplitude of 1, the phase angle of 0, and the frequency of ω, and the remained two disturbances are assumed to be zero. (3) The cavity surface temperature is regarded with the amplitude of 1, the phase angle of 0, and the frequency of ω, and the remained two disturbances are assumed to be zero. When the disturbance is specified, the frequency characteristics of the hollow block ventilated wall can be calculated easily by using the FDFD model and the RC model under various disturbances.

3. Case study

3.1. The selection of the calculation parameters

The size of hollow block is 390 × 190 × 190 (mm), and the cavity size is 250×100mm (length × width). Meanwhile, the typical meteorological parameters of Wuhan city in summer are chosen, and other thermal parameters can refer to the following: (1) Convection heat transfer coefficient of internal and external surface of the concrete are 8.6 and 18.3 W/(m^2.K), respectively. (2) Convection heat transfer coefficient between the air and the cavity surface can be calculated by the equation: $h = 4.8 + 3.4v$, $v \le 5m/s$ .When the airflow velocity is 1 m/s, it is 8.2W/(m2.K). (3) The thermal conductivity of concrete wall is 1.74 W/(m.K). (4) The emissivity of the reinforced concrete ε is 0.95εn, where ε_n is the normal emissivity, here 0.94 is taken so ε is 0.89.

3.2. The results of identified parameters by using Genetic Algorithm

For conciseness and space saving, only the frequency characteristics of this structure imposed by the solar air temperature disturbance within the frequency range of normal concern (10^{-8} to 10^{-3} rad/s) by using the FDFD model and the RC model is presented and analyzed. The results of identified parameters by using GA are shown in Table 1.

Table. 1. Identified parameters of simplified RC model of the hollow block ventilated wall.

Parameters of resistance, R ($m^2 \cdot K \cdot W^{-1}$)								capacitance, C($J \cdot m^{-2} \cdot K^{-1}$)	
R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8	C_1	C_2
0.025	0.029	0.0008	0.102	0.102	0.01	0.0002	0.025	103819	185745

$$\begin{bmatrix}
\frac{1}{R_w}+\frac{1}{R_1} & 0 & -\frac{1}{R_1} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & \frac{1}{R_w}+\frac{1}{R_1} & 0 & -\frac{1}{R_1} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{R_8} & 0 & \frac{1}{R_{in}}+\frac{1}{R_8} & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{R_8} & 0 & \frac{1}{R_{in}}+\frac{1}{R_8} \\
0 & 0 & \frac{2A_3}{R_2} & 0 & 0 & 0 & 0 & 0 & \frac{A_2}{R_7} & 0 & -(\frac{A_2}{R_7}+\frac{2A_3}{R_2}+\frac{A_1}{R_8}) & A_1C_2\omega & \frac{A_1}{R_8} & 0 \\
0 & 0 & 0 & \frac{2A_3}{R_2} & 0 & 0 & 0 & 0 & 0 & \frac{A_2}{R_7} & -A_1C_2\omega & -(\frac{A_2}{R_7}+\frac{2A_3}{R_2}+\frac{A_1}{R_8}) & 0 & \frac{A_1}{R_8} \\
0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{R_5} & 0 & -(\frac{1}{R_5}+\frac{1}{R_7}) & 0 & \frac{1}{R_7} & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{R_5} & 0 & -(\frac{1}{R_5}+\frac{1}{R_7}) & 0 & \frac{1}{R_7} & 0 & 0 \\
0 & 0 & \frac{1}{R_3} & 0 & -(\frac{1}{R_3}+\frac{1}{R_4}) & 0 & \frac{1}{R_4} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & \frac{1}{R_3} & 0 & -(\frac{1}{R_3}+\frac{1}{R_4}) & 0 & \frac{1}{R_4} & 0 & 0 & 0 & 0 & 0 & 0 \\
\frac{A_1}{R_1} & 0 & -(\frac{A_1}{R_1}+\frac{2A_3}{R_2}+\frac{A_2}{R_3}) & A_1C_1\omega & \frac{A_2}{R_3} & 0 & 0 & 0 & 0 & 0 & \frac{2A_3}{R_2} & 0 & 0 & 0 \\
0 & \frac{A_1}{R_1} & -A_1C_1\omega & -(\frac{A_1}{R_1}+\frac{2A_3}{R_2}+\frac{A_2}{R_3}) & 0 & \frac{A_2}{R_3} & 0 & 0 & 0 & 0 & 0 & \frac{2A_3}{R_2} & 0 & 0 \\
0 & 0 & 0 & 0 & -\frac{1}{R_4} & 0 & \frac{1}{R_4}+\frac{1}{R_5}+\frac{1}{R_6} & 0 & -\frac{1}{R_5} & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & -\frac{1}{R_4} & 0 & \frac{1}{R_4}+\frac{1}{R_5}+\frac{1}{R_6} & 0 & -\frac{1}{R_5} & 0 & 0 & 0 & 0
\end{bmatrix}
\begin{bmatrix} u_{out} \\ v_{out} \\ u_1 \\ v_1 \\ u_1' \\ v_1' \\ u_w' \\ v_w' \\ u_2' \\ v_2' \\ u_2 \\ v_2 \\ u_{in} \\ v_{in} \end{bmatrix}
=
\begin{bmatrix} \frac{1}{R_w}u_{out}' \\ \frac{1}{R_w}v_{out}' \\ \frac{1}{R_{in}}u_{in}' \\ \frac{1}{R_{in}}v_{in}' \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ \frac{u_w}{R_6} \\ \frac{v_w}{R_6} \end{bmatrix}
\tag{15}$$

Fig. 4 shows the temperature calculated by using the FDFD model and the RC model respectively of different surfaces under solar air temperature disturbance. The two results match well so the established RC model is reliable.

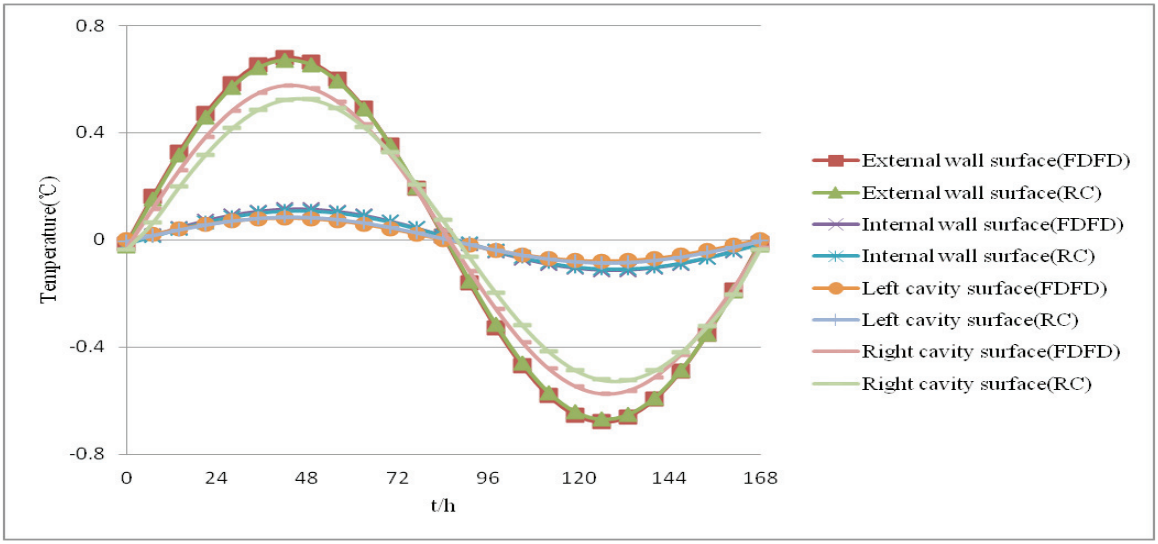

Fig. 4. The temperature of different surfaces under solar air temperature disturbance.

4. Frequency characteristics responses analysis by using the RC model

Fig. 5 and Fig. 6 show the frequency responses of the heat flux on the external wall surface, internal wall surface and the internal cavity surface when the solar air temperature disturbance is imposed on it. As can be seen from the Figures, the frequency responses of the heat flux of these three surfaces change when the frequency changes. In the low and medium frequency regions, the frequency responses are not obvious, almost remain stable. But in the high frequency regions, the frequency responses are very clear. The phase angle of the heat flux on the external wall surface is greater than 0, and it means the responses advance. The phase angle of the heat flux on the internal wall surface and the internal cavity surface are less than 0, and it means the responses lag.

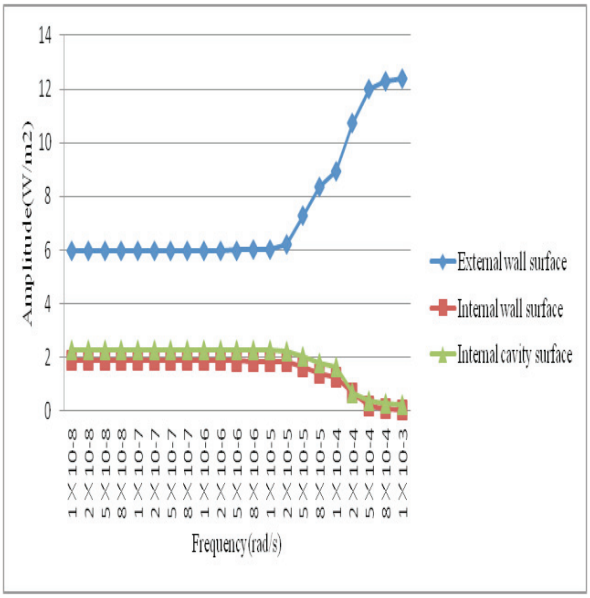

Fig. 5. Amplitude of the heat flux on three surfaces.

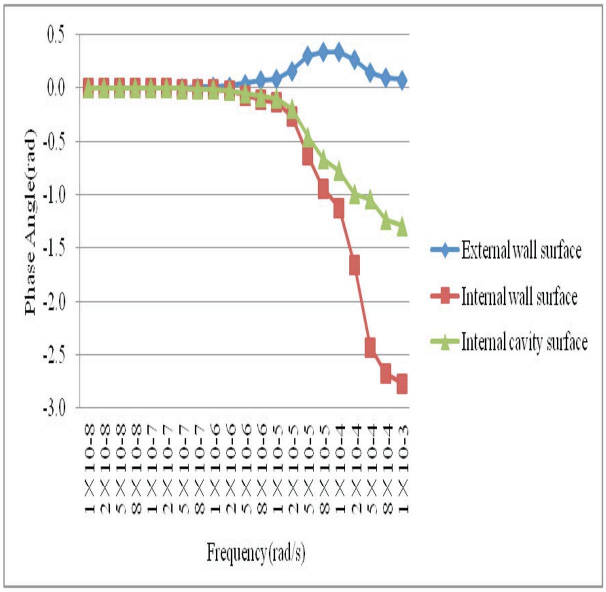

Fig. 6. Phase angle of the heat flux on three surfaces.

5. Methods

In this paper, a simplified dynamic thermal network model of the hollow block ventilated wall is proposed using thermal resistance and capacity (RC)-network method. Then, the theoretical frequency thermal performance which is calculated by frequency-domain finite difference (FDFD) model is as a reference, and the parameters of the simplified model are identified by using a genetic algorithm (GA).

6. Results

The thermal performance of the hollow block ventilated wall under solar air temperature disturbance is calculated using FDFD model and RC model, respectively. The temperatures of the external wall surface, internal wall surface and the cavity surface calculated by the two methods match well. This indicates that the RC model can well predict the thermal characteristics of the hollow block ventilated wall. The thermal performance of the ventilated wall is studied using the RC model, results show that when the disturbance frequency is changed, the thermal response of the external wall surface, internal wall surface and the cavity surface also changes. In the low and medium frequency regions, the amplitude and phase angle of the heat flux on the three surfaces change small, almost keep steady. But in the high frequency regions, the amplitude and phase angle of the heat flux on the three surfaces change greatly.

7. Discussion

This paper presents a simplified dynamic thermal network model for the hollow block ventilated wall since a simplified thermal model is the best candidate for modelling the dynamic thermal behaviours and integration in conventional energy and indoor environment simulation packages. Furthermore, the frequency responses of the heat flux on the external wall surface, internal wall surface and the internal cavity surface under the solar air temperature disturbance are also analyzed. The results show that the amplitude and phase angle of the heat flux on the three surfaces change greatly in the high frequency regions while they almost keep the same in the low and medium frequency regions. This is believable because the frequency response of the heat flux of conventional wall is high-frequency response.

8. Conclusions

The simplified dynamic thermal network model established in this paper can analyze the dynamic heat transfer characteristics of the hollow block ventilated wall well. Furthermore, when the model is integrated with normal simulation program of building energy consumption, energy saving potential and suitability of the hollow block ventilated wall for different places can be studied. This can be beneficial to the application and promotion of the wall.

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